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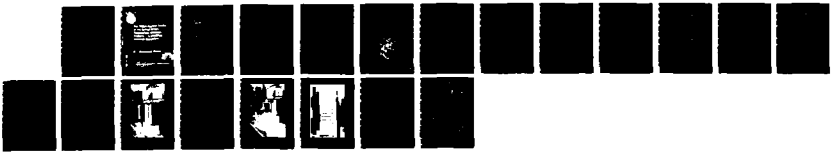

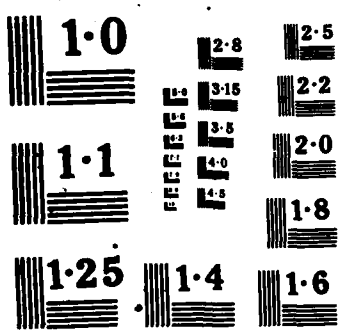

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This publication provides a simplified technical description of the research reactor at AFRRI. Topics covered include Principles of Reactor Operation, The AFRRI Reactor Versus a Power Reactor, Modes of Operation, The AFRRI Reactor, Exposure Facilities, and Cerenkov Radiation.

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The mission of the Armed Forces Radiobiology Research Institute (AFRRI) is to conduct research in the field of radiobiology and related matters that is essential to the operation and medical support of the Department of Defense and the Military Services. In support of ~~that~~ mission, AFRRI operates a medium-sized research nuclear reactor. The reactor is used to generate radiations, primarily neutrons and gamma rays, which are used to conduct experimental biomedical research and to produce isotopes. The radiations are delivered to the experiments in one of two ways: A pulse operation delivers a very short burst of high power, or a steady-state operation delivers a longer, continuous low- to medium-power exposure. The reactor is also used to train military personnel in reactor operations.

The AFRRI TRIGA Mark-F reactor facility is within the AFRRI complex on the grounds of the Naval Medical Command National Capital Region, in Bethesda, Maryland. TRIGA is an acronym for Training, Research, and Isotope, General Atomics. Mark-F is the specific General Atomics Reactor model, distinguished by a pool, a movable core, exposure room facilities, and the ability to pulse to momentary high powers. A cutaway view of the AFRRI reactor is shown in Figure 1.

Reactor operations at AFRRI began in 1962. In 1965, a change was made from aluminum-clad to stainless steel-clad fuel elements. Currently more than 150 multiple-exposure experiments are performed each year using the reactor.

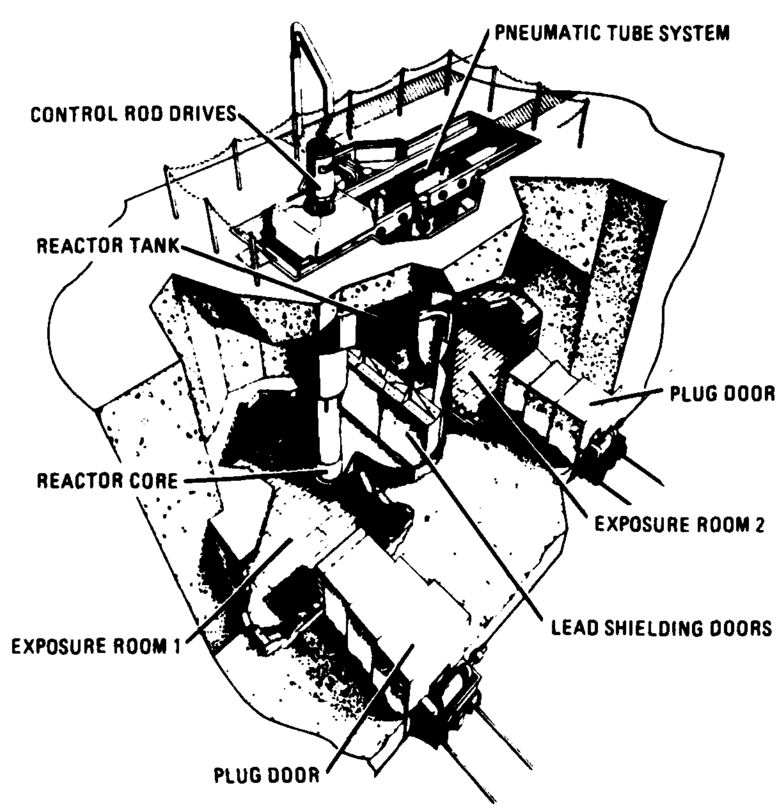

Figure 1. Cutaway view of AFRRI TRIGA reactor

PRINCIPLES OF REACTOR OPERATION

The process of splitting the nucleus of a heavy atom is called fission. Certain elements are ideal for fission because their nucleus splits easily upon absorption of low-energy neutrons. Uranium-235 is such an element, and it is used as fuel in the AFRRI reactor as well as commercial power reactors. When a neutron enters the nucleus of a uranium-235 atom, it disrupts the stability of the nucleus and causes the nucleus to split, generally into two fragments. As fission occurs, neutron, beta, and gamma radiations are emitted, along with other photons and particles. After slowing down in energy, some of the neutrons that result from the fission will enter the nuclei of additional uranium-235 atoms and cause further fissions. If allowed to continue, the resulting series of fissions is called a chain reaction (see Figure 2). The fragments resulting from the fission process have large amounts of kinetic energy, and that energy is transferred to the surrounding medium in the form of heat energy.

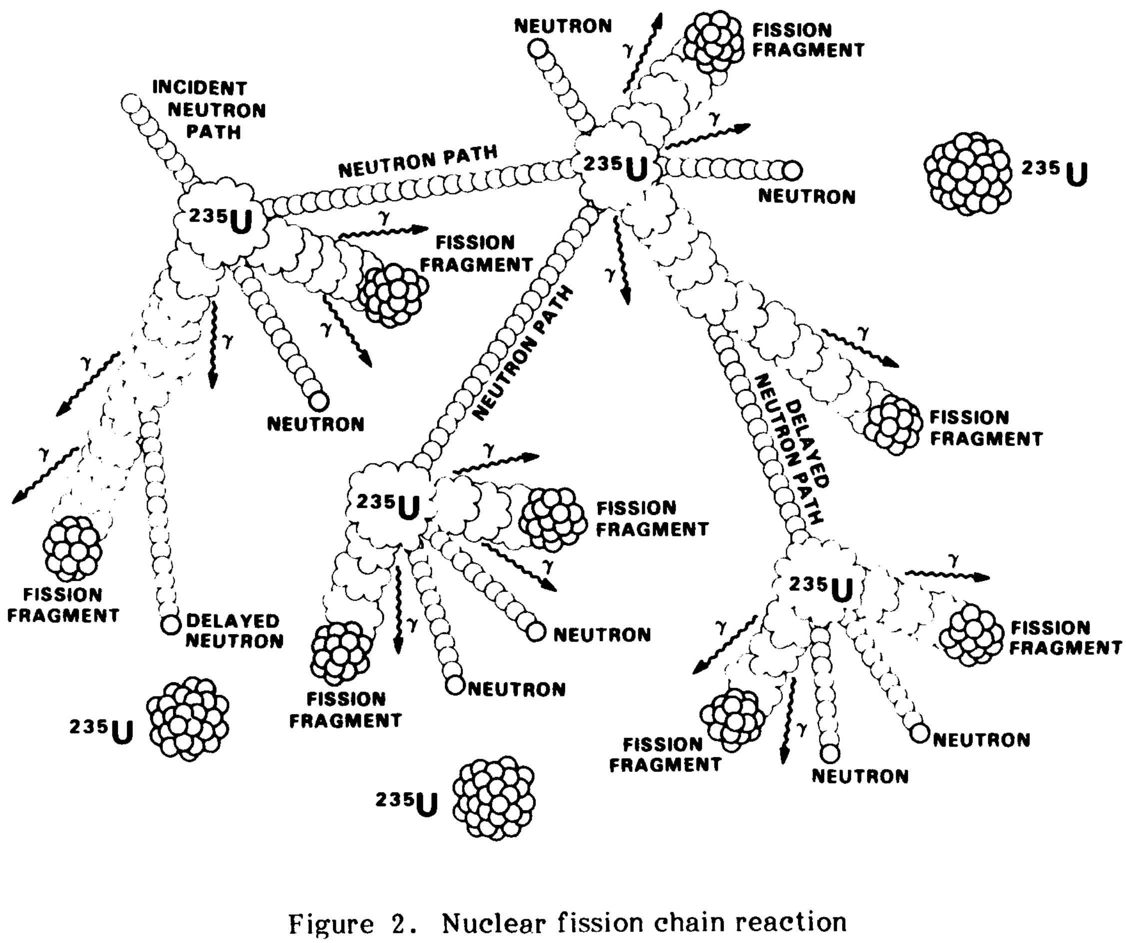

Figure 2. Nuclear fission chain reaction

THE AFRRI REACTOR VERSUS A POWER REACTOR

The AFRRI reactor, classified as a 1-megawatt research reactor, differs from a power reactor in purpose and usage. The AFRRI reactor serves as a source of radiation, mainly neutrons and gammas, for research purposes. The heat energy produced by the fission process is not of concern at AFRRI, because the nominal amounts of heat produced by the AFRRI reactor are dissipated in its cooling system. In contrast, power reactors depend on the heat produced, and channel the heat resulting from fission into steam turbines, which then turn generators to produce power. Conversely, the radiation produced in a power reactor is an unwanted by-product, and must be appropriately controlled. The relative amounts of heat and radiation produced by the AFRRI reactor and a power reactor may be compared in terms of power levels of operation. The AFRRI reactor operates at a maximum of 1 megawatt (thermal), while a power reactor typically operates at power levels of 1000 megawatts electrical or about 3000 megawatts thermal. Power reactors, as all reactors, directly produce thermal power, which is then converted into electrical power at about 30 percent efficiency.

MODES OF OPERATION

The power levels of a reactor directly correspond to the rate at which fission occurs. In turn, the rate of fission is governed by the size of the neutron population in the core (Figure 1). As the neutron source perpetually emits neutrons, and as prompt and delayed neutrons are constantly produced from fission, new neutron generations continually occur in the reactor core. The reactivity of the core is described in terms of criticality; that is, when the number of neutrons from generation to generation is constant, the reactor is said to be critical. When the neutron population is decreasing, the reactor is said to be subcritical. When the neutron population is increasing, the reactor is said to be supercritical.

The AFRRI reactor is licensed to operate in a variety of power levels, which are characterized by two modes: steady-state mode and pulse mode. Each of these operational modes is accompanied by particular power levels and individual configurations of control rods (the transient rod, safe rod, shim rod, and regulating rod). Each mode simulates a general type of radioactive occurrence or dose delivery to the experiment, described as follows.

STEADY-STATE MODE

The steady-state mode is characterized by low levels of power, up to 1 megawatt, which occur for a designated length of time, from several seconds to hours. The reactor may be automatically set to shut down after a particular amount of time, or it may be manually shut down after achieving a desired radiation dose in an exposure facility. In the steady-state mode, the reactor is brought to a specific power, and is then controlled to run constantly at that power until shut down. The reactor is brought to power by first partially withdrawing the transient rod, then partially withdrawing the safe rod and shim rod, and finally withdrawing the regulating rod a sufficient amount to produce the power sought. Depending on the position of the core, the rod heights may be adjusted so that the majority of the radiation is thrown in a particular direction. The steady-state mode simulates a relatively low-level, long-term exposure to radioactivity.

PULSE MODE

The pulse mode is characterized by a rapid rise in power, up to 3000 megawatts. In order to be able to pulse the reactor, or bring the power to momentary high levels, the reactor must first be brought to criticality at a low level of power. In order to accomplish this, the safe rod and shim rod are usually completely withdrawn and the regulating rod is partially withdrawn so that the reactor will be steady at the desired power. Following this, calculations are made of the rod drive position for the required pulse value, and the anvil (part of the rod drive that limits upward movements) is raised to the appropriate height. The transient rod is then fired, driven by compressed air. The transient rod hits the anvil, and the anvil drops down by the force of gravity. This is followed automatically by shutdown of the reactor. The entire process takes place in less than 500 milliseconds, and results in a short burst of high-level radiation.

THE AFRRI REACTOR

REACTOR CORE

The core (see Figure 1) is the heart of a reactor. The core is composed primarily of fuel elements (containing the uranium fuel), a neutron source, and neutron-absorbing control rods. The core is the site of fission, which produces the radiation sought by research investigators. The AFRRI reactor is equipped with a movable core. The core is suspended under 16 feet of water from a dolly just above the reactor pool. Movement of the core dolly along the track from one side of the pool to the other is controlled from the reactor console. Approximately 5 minutes are required to move the core from one side of the pool to the other, a distance of 13 feet.

Located next to the base of the tank pool (two floors below the control room) are two exposure rooms (Figure 1). Exposure rooms are dry exposure areas into which experiments are placed. One is located at each end of a pool shaped like a cloverleaf. The advantages to having a movable core are that (a) the quantity and character of the radiation reaching these exposure facilities may be controlled, and (b) more than one exposure facility may be used at the same time. The primary types of radiation produced by the AFRRI reactor are neutron and gamma. The ratio of neutron radiation to gamma radiation may be controlled by movement of the core and by shielding. In order for personnel to enter an exposure room to set up or change experiments, the core is moved to the opposite side of the pool. The lead shield doors are then closed for additional shielding.

The core support structure provides a means to suspend the reactor core. The core housing structure encloses the control rod drives (Figure 1), which are gear systems to lower or withdraw the control rods into or from the core. Connecting rods connect the rod drives to the actual control rods, which are located within the core, 16 feet under water.

As stated, the core is composed of cylindrical fuel elements, control rods, and a neutron source held in place by two grid plates. In each grid plate (see Figure 3), holes for the fuel elements and control rods are arranged in six concentric rings labeled A thru F. The four control rods occupy four holes, and 87 fuel elements occupy the remaining holes. A guide tube to hold the neutron source is placed immediately outside the sixth or "F" ring.

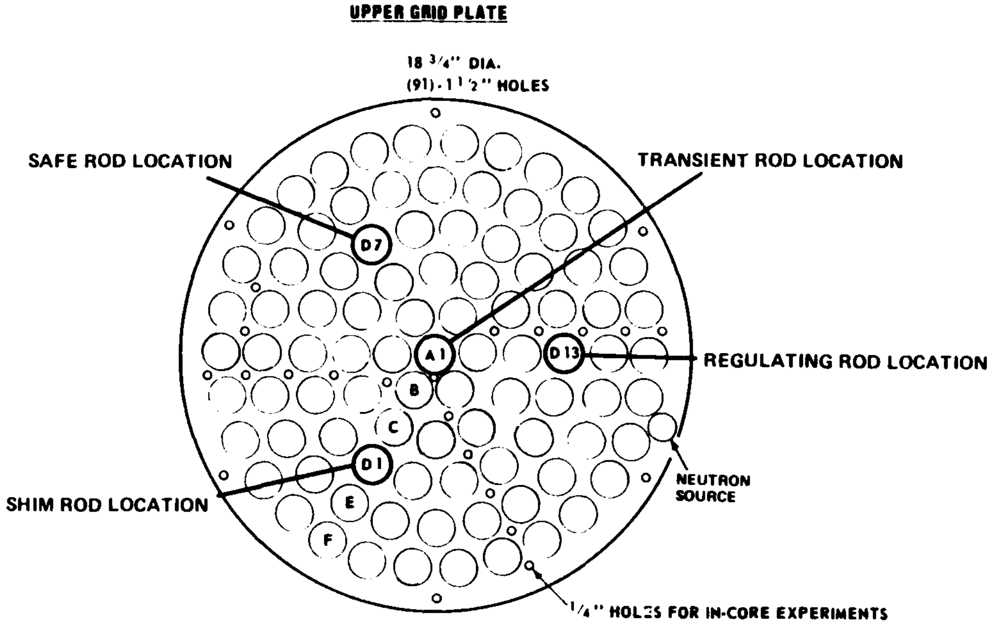

Figure 3. Overhead view of AFRRI reactor. Remaining holes are filled with 87 fuel elements.

FUEL ELEMENTS

An AFRRI TRIGA fuel element is shown in Figure 4. The fuel elements are principally composed of a cylinder of zirconium hydride mixed with uranium-235, the actual fuel of the reactor. Uranium-235 will fission upon the absorption of neutrons, thereby producing more neutrons as well as gamma radiation and heat. Uranium-235 has a much greater probability of absorbing a low-energy or "slow" neutron than a fast neutron. As a result, zirconium hydride, a moderator, is used to slow down the fast neutrons emitted from the neutron source and the fissioning uranium-235. A rod of zirconium is placed inside the fuel cylinder to ensure structural integrity. Graphite plugs are placed at each end of the fuel element in order to reflect fast neutrons back into the core, which then requires fewer fissions to sustain the chain reaction.

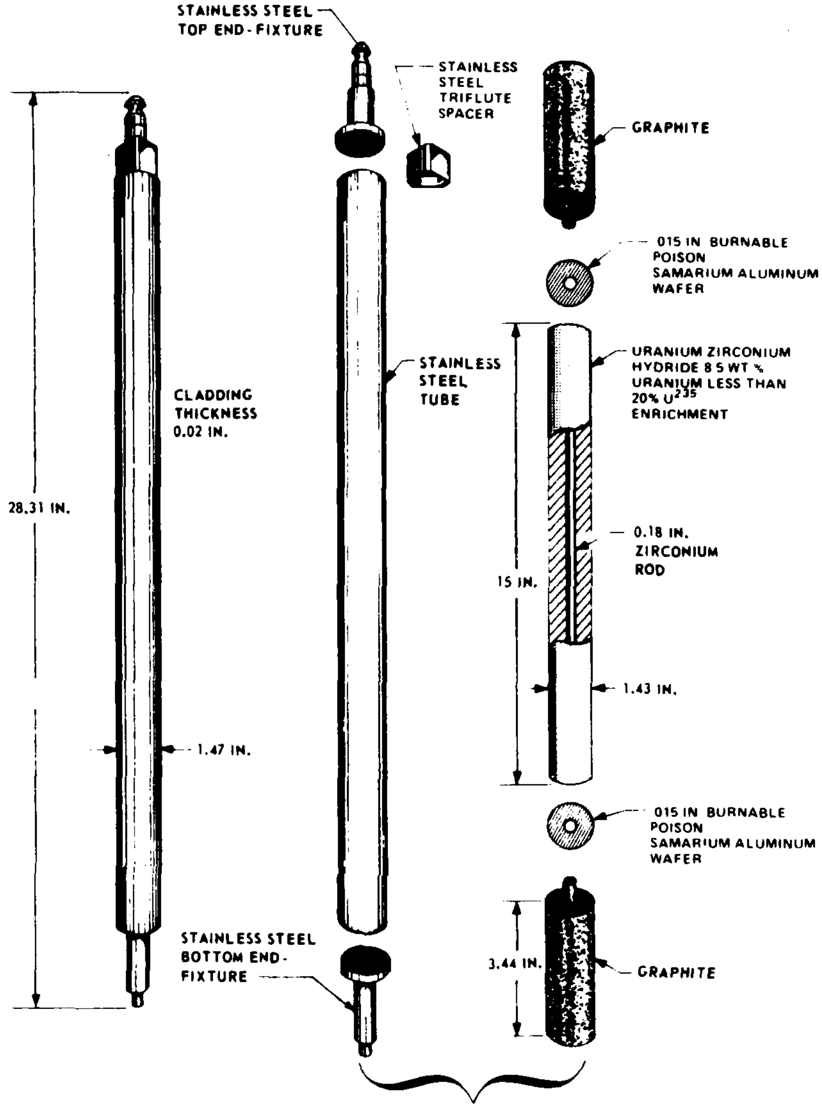

Figure 4. Standard fuel element

Samarium wafers are placed between the fuel cylinder and the graphite plugs, in order to extend the life of the fuel elements. The wafers do so because they absorb neutrons and burn out in proportion to the rate of fuel burnup.

An instrumented fuel element is similar in construction to a standard fuel element. It differs in that three thermocouples are placed within the center portion of the fuel element. These thermocouples measure the temperature of the fuel, which is then monitored at the reactor console.

CONTROL RODS

To be of maximum use in experimentation, the rate of fission must be controlled, thereby controlling the amounts of radiation and heat that are generated. The fission rate is controlled by absorbing the neutrons resulting from fission, thus decreasing the number of neutrons available to the fuel elements for subsequent fissioning. In the AFRRI reactor, the absorption of neutrons is regulated by control rods, which are mainly composed of borated graphite. (Boron is an effective neutron absorber, and graphite is a viable means for the suspension of boron, which is brittle and powdery in pure form.) These control rods are moved in or out of the core by means of rod drives, which are operated from the reactor console. The amount of control rod present in the core regulates the fission rate. That is, a greater length of control rod in the core results in a greater number of absorbed neutrons and, finally, a lower fission rate. If neutrons are being absorbed at a greater rate than they are being produced, the fissions will decrease and the production of power and radiation will be terminated. On the other hand, if neutrons are being produced at a faster rate than they are being absorbed, the fissions will increase along with the power level and corresponding radiations. By withdrawing just enough of the control rods to match the neutron absorption rate with the neutron production rate, a steady-state power level may be achieved.

As mentioned, there are four control rods in the core of the AFRRI reactor. One control rod is placed in the center position (Figure 3) called the "A" ring, and three are placed evenly in the fourth ring or "D" ring of the reactor core. The control rods in the fourth ring are the safe rod, shim rod, and regulating rod, known as standard rods. From the console, an operator may drive these rods slowly up and down. He may also "scram" the rods, allowing them to drop by means of gravity back into the core of the reactor. The control rod in the center ring is called the transient rod. This rod may be driven up and down in the same manner as the other control rods. In addition, the transient rod may be fired out of the core by means of compressed air. Before firing, a stopping anvil is appropriately positioned above the transient rod. Upon firing, the transient rod lifts from the core and hits a shock-absorbing anvil. The reactor is now in pulse mode, that is, ready for a brief high-power excursion. In pulse mode, all control rods will scram after a brief period of time set by the operator, usually 500 milliseconds. When the reactor is in steady-state mode, the rod stays against the anvil and is used like a standard rod. The standard and transient control rods are shown in Figure 5.

NEUTRON SOURCE

A neutron startup source is necessary to ensure the constant availability of neutrons in the core, in order to begin a power increase. The neutron source is composed of a mixture of americium and beryllium, doubly encased in stainless steel. Neutrons are produced by this source in the following manner: Americium, a man-made element, spontaneously decays into neptunium and alpha particles. Alpha particles react with the light element beryllium to produce carbon and high-energy neutrons, known as fast neutrons. These neutrons (also called source neutrons) are needed in the core for the control of fission as the control rods are withdrawn to increase power. Without a population of source neutrons in the core, fission could occur only spontaneously, and spontaneous fission cannot be predicted or controlled.

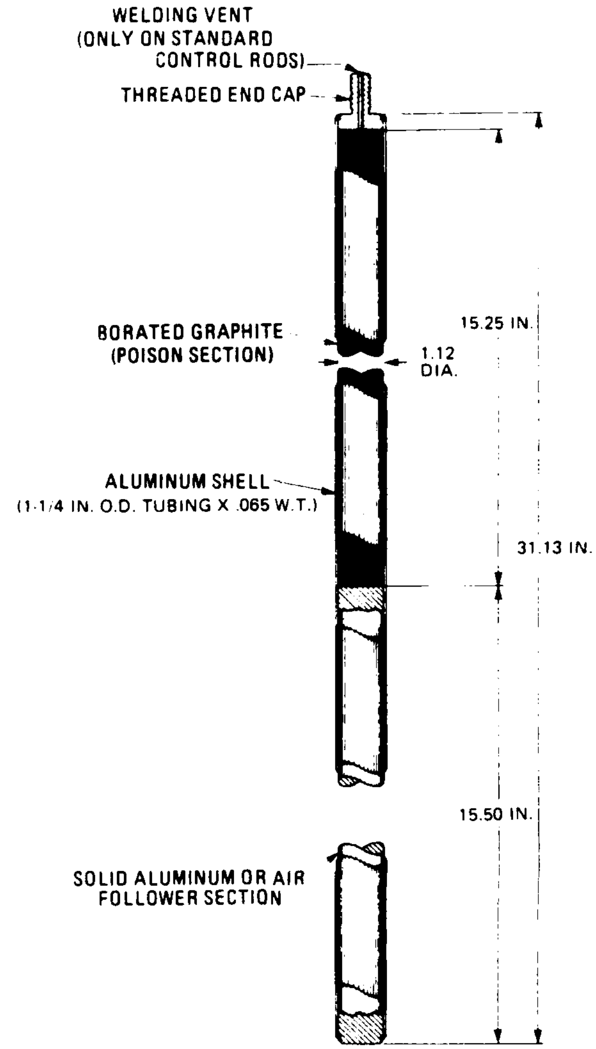

Figure 5. Standard and transient control rod

MODERATION

The AFRRI reactor has an inherent safety feature that will terminate (with or without control rods) a large and rapid rise of power (or an excursion, as it is known in reactor terms). This safety feature is based on the fact that to continue to produce enough neutrons to sustain power, neutrons must "slow down" to very low energy from the high energy at which they are born. As power is produced, heat (from fissioning) is transferred into the zirconium hydride, making it hot. When heated, the zirconium hydride does not allow the neutrons to cool to thermal energy, which in turn does not allow fissioning to occur. Without fissioning, the reactor power is terminated, because it is the heat from fission that produces thermal power. This inherent mechanism, built into the TRIGA fuel, makes an explosion or "meltdown" physically impossible.

INSTRUMENTATION

Instrumentation is placed in and around the core in order to measure and communicate information that is helpful in maintaining control over the operations of the reactor. The population levels of neutrons in and above the core are measured by detectors called ion chambers, which contain boron and are sensitive to neutrons. Also, the gamma level is measured during a reactor pulse by ion chambers that are sensitive to gamma. In addition, the temperatures of the reactor core and the pool must be monitored and controlled. To do this, thermocouples placed within the two instrumented fuel elements measure the fuel temperature, and two thermistors placed in the reactor pool measure the water temperature. One thermistor is positioned directly above the core, and one is positioned a few feet below the surface of the water, near the side of the pool.

COOLING SYSTEMS

The reactor core sits in a "swimming" pool. The pool acts as a radiation shield, protecting operation personnel from radiation. Water is an effective medium for shielding from neutron radiation, because neutrons generally travel only a foot or two in water. Gamma radiation is also greatly attenuated by water, with 16 feet of water being more than sufficient for an effective radiation shield.

In addition to protecting personnel from radiation, water in the pool serves as a means of cooling the reactor core. During operation of the reactor, heat energy is passed from the core to the surrounding water, and the water is then passed through a cooling system. From there, heat is transferred through heat exchangers to a secondary water system, and is then dissipated in the cooling towers. The water system for the reactor also provides cleaning and filtration of the water in the pool. There, filters eliminate particulate matter to maintain optical clarity in the pool. In addition, a demineralizer removes mineral ions to prevent the activation (or irradiation) of ions, which occurs naturally in water.

LEAD SHIELD DOORS

Two lead shield doors are located at the bottom of the reactor pool. The doors are aluminum shells 19 inches thick, 5 feet high, and 6 feet wide. They are filled with lead shot and transformer oil. The doors must be opened to allow movement of the core from one side of the pool to the other. They may be closed to provide shielding for scientific personnel working in the exposure rooms on the opposite side of the doors from the core. The doors rotate around aluminum poles. The poles are parallel to each other in the open position, and their edges overlap in the closed position. The edges of the doors are stepped (designed to overlap) to prevent the streaming of radiation from between the doors.

EXPOSURE FACILITIES

The Reactor has several exposure facilities for the irradiation of specimens. The AFRRI reactor has two exposure rooms, an extractor tube system, a core experiment tube, a portable beam tube system, and a pneumatic transfer system. Each of these facilities possesses unique features and provides variety in the reactor research capabilities at AFRRI. They are described in the following paragraphs.

EXPOSURE ROOM 1

Exposure Room 1 is located north of the pool, and is the most frequently used facility. The room possesses several arrays (or varieties) in shielding, which make it especially useful to investigators. The exposure room is 23 feet square and 9 feet high, with a semicylindrical section of the aluminum pool wall projecting through the south wall of the room. The reactor core can be moved to within less than 1 inch of the aluminum tank wall, separated from the tank wall by water. A cadmium-gadolinium shield is positioned on the tank projection, to absorb the leakage of thermal neutrons from the core into the exposure room. Lead curtains are suspended from the ceiling to prevent the scattering of gamma rays into Exposure Room 1 when the core is operating on the opposite side of the pool near Exposure Room 2. The walls and ceiling of Exposure Room 1 are made of concrete, covered with wood and painted with gadolinium paint. Because fast neutrons can activate concrete and thus present a hazard to personnel, the concrete is covered by wood. The wood slows down the fast neutrons emitted from the core, thus drastically reducing the chances of activating the concrete. After being slowed down or "thermalized" by the wood, the neutrons may bounce back toward the interior of the room, but are then absorbed by the gadolinium paint before they can escape into the room. The tank wall as seen from ER 1 is shown in Figure 6.

EXPOSURE ROOM 2

Exposure Room 2 is similar to Exposure Room 1 in construction. The room is slightly smaller, but the ceiling and walls follow the same design as those of Exposure Room 1: concrete walls covered with wood painted with gadolinium paint. The pool wall projects from the north wall of Exposure Room 2 just as in Exposure Room 1, but it is not shielded with cadmium. As a result, a high concentration of thermal neutrons enters the exposure room. This differs from the neutron concentration in Exposure Room 1, in which the neutron population is composed primarily of fast neutrons. Experiments needing a high thermal neutron component are exposed in this room.

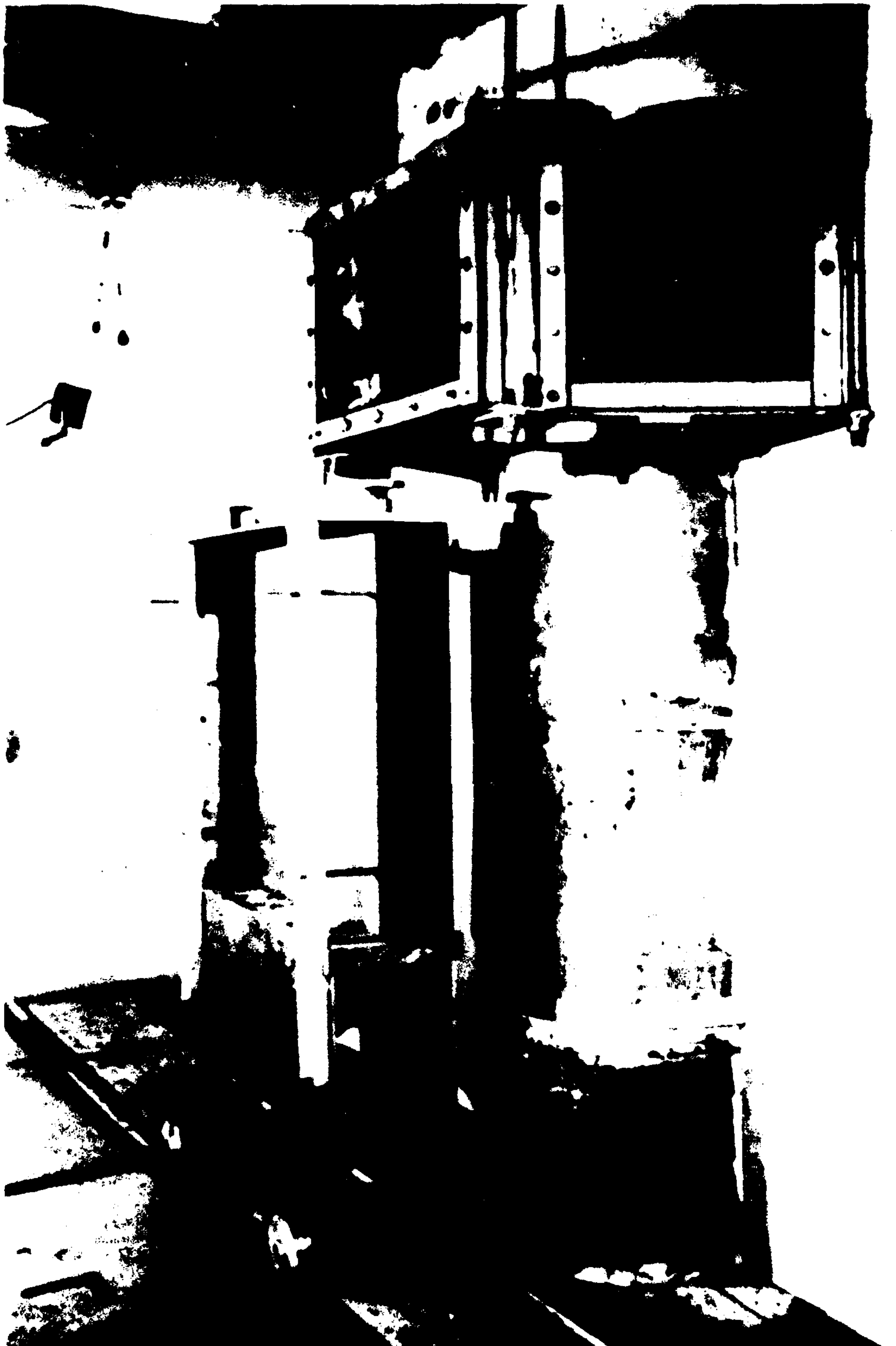

Figure 6. ER-1 tank wall with Pb shield

SHIELDING

Within the two exposure rooms, exposure to radiation can be tailored or modified by means of shielding. Shielding materials, which are often part of experimental setups (or arrays) consist of lead bricks, or bismuth bricks, or combinations of both. Currently a lead shield and a lead cave are often used together. Lead serves as a shield from gamma radiation. Placed in the path of radiation, it will enhance the relative neutron field on the other side. The lead shield is placed in front of the reactor core to shield samples from gamma rays that are emitted from the core. The lead cave is placed behind the lead shield in order to shield samples from gamma radiation that scatters from the exposure room walls. This shield-and-cave setup is shown in Figure 7. The result is a miniature lead chamber containing an enhanced neutron field. Samples inside this chamber may be placed in rotators, which aid the even bilateral exposure of specimens. The standard rotator for small specimens is shown in Figure 8. In both the lead shield and the lead cave, the thickness of the lead may be altered, to produce further variety in radiation fields.

Bismuth serves the same purposes as lead: to shield from gamma rays and to provide an enhanced neutron field. But bismuth is more useful than lead because, although both absorb neutrons, bismuth does not emit gamma rays and lead does. Because bismuth emits alpha particles upon the absorption of neutrons, the bricks are painted to shield from alpha radiation.

In addition to placing shielding materials within the exposure rooms, the amount and character of radiation reaching the samples in the exposure rooms may be modified by moving the reactor core. Moving the core away from an exposure facility places more water between the core and that exposure room. This results in a smaller number of neutrons reaching the exposure room, and those that do are generally of a lower energy. Therefore, the radiation field in that facility contains a higher percentage of gamma radiation.

EXTRACTOR TUBE SYSTEM

Exposure Room 1 is equipped with an extractor tube system, which permits the quick insertion and withdrawal of samples. When in position, the extractor tube extends from directly in front of the core, through the west wall, and into the prep area, outside of the exposure room. The section of the tube in the wall follows an "S" curve, which prevents the radiation from streaming from the exposure room into the prep area. Samples are placed inside a plastic carrier and positioned within the tube by means of a motorized pulley system, controlled from the prep area. The quick retrieval of samples from the exposure room results in greater precision in evaluating the amount of radiation received by the samples, particularly for low-level exposures. This eliminates time delays in moving the reactor core, closing the lead shield doors, and opening the exposure room doors. Experimental retrieval takes place in seconds rather than the tens of minutes required for full procedures of room entry. The extraction also reduces the exposures to personnel that result from exposure room entries.

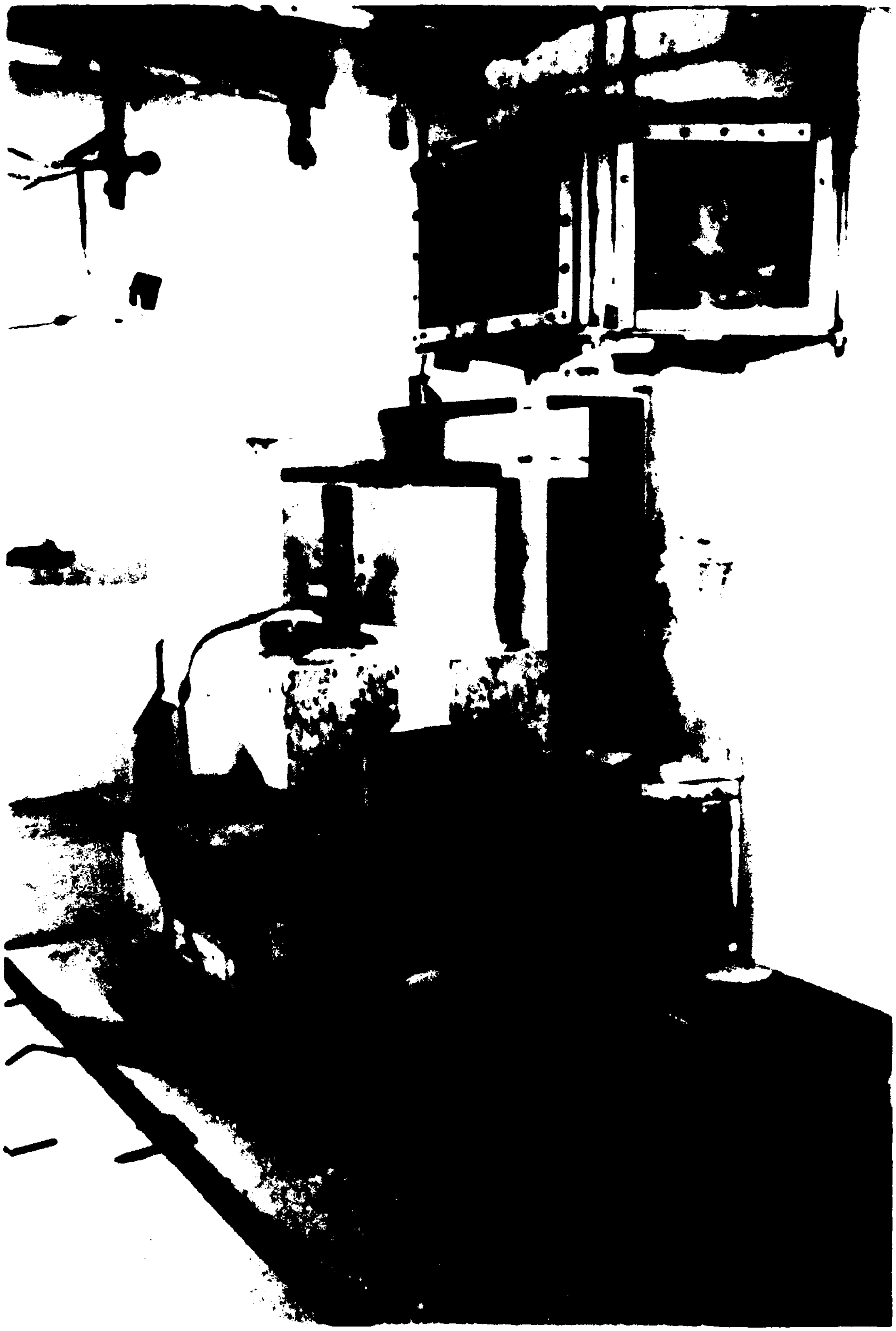

Figure 7. Setup of shield and lead cave

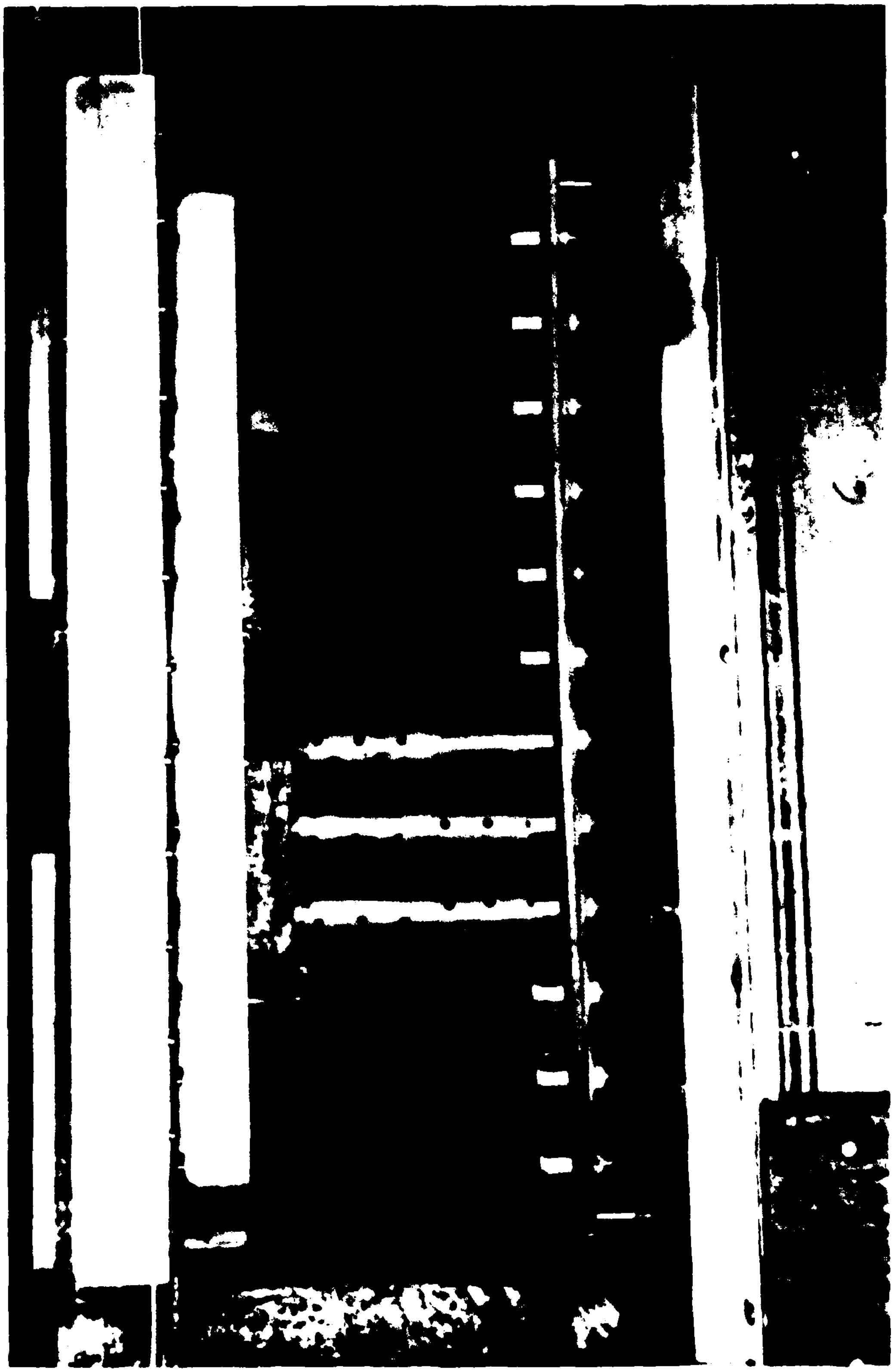

Figure 8. Standard rotator for small specimens

CORE EXPERIMENT TUBE

Samples may be irradiated in the exposure rooms, or they may be irradiated in the core itself, by means of the Core Experiment Tube. The Core Experiment Tube is a hollow aluminum tube with an "S" bend to prevent streaming of radiation. In this procedure, a fuel element is withdrawn from the core and placed in storage, and a Core Experiment Tube is placed in that fuel element location. The samples to be irradiated are placed in small polyethylene containers, called "rabbits," which are then loaded into the tube and placed directly into the core. The rabbits may be withdrawn with a modified fishing pole. The Core Experiment Tube is used primarily to produce isotopes, which are used by researchers as biological tags or tracers. Radioactive potassium is the isotope most commonly produced. Materials may be activated in the Core Experiment Tube, and the patterns of radiation emitted following activation may be used to analyze those materials. This process has several applications.

PORTABLE BEAM TUBE SYSTEM

The portable beam tube system consists of aluminum tubes suspended in the reactor containment pool. A beam of radiation is produced by this system, thus allowing the irradiation of selected areas of specimens. A variety of filters and lenses may be incorporated into experiments to vary the degree, character, and precision of the radiation.

PNEUMATIC TRANSFER SYSTEM

The AFRRI reactor also possesses a pneumatic transfer system. The system is not in use at the present time, but it may be reinstalled quickly if the need arises to produce extremely high activities of radioisotopes.

CERENKOV RADIATION

Cerenkov radiation is a bright blue color that appears around the reactor core. It accompanies a reactor pulse and also steady-state operations above 1 kilowatt. As fission occurs, charged beta particles are emitted, in addition to all other fission products. With enough energy, these beta particles travel at a speed greater than the speed of light in the given medium (water). As these particles slow down, excess energy is given off as photons of light, which are observed as a bright blue glow.

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